Cleanroom Air Systems Design

William Tschudi
June 22, 2004
WFTschudi@lbl.gov
510-495-2417

PUBLIC INTEREST ENERGY RESEARCH
"Research Powers the Future"

BERKELEY LAB

Today's session

- Plan to focus on energy efficiency of cleanroom air systems.
- Concepts rather than "how to"
- What does this audience want to know?
- What is the audience background?
- What industries/institutions are represented?
- New construction or retrofit?

Session outline

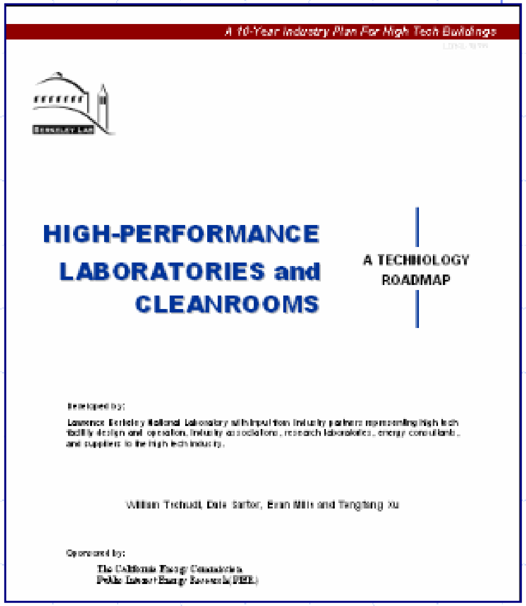
- Background on LBNL’s work
- Examples of air system designs
- Cleanliness standards
- Cleanroom programming guide
- Savings by design cleanroom baseline criteria
- Air systems benchmark results
- Air change rates

session outline (continued)

- Fan-filter selection
- Case Study
- Summary
  - Multi-discipline issues – whole building approach
  - "Best practices" from initial benchmarking
  - The big issues
- Resources

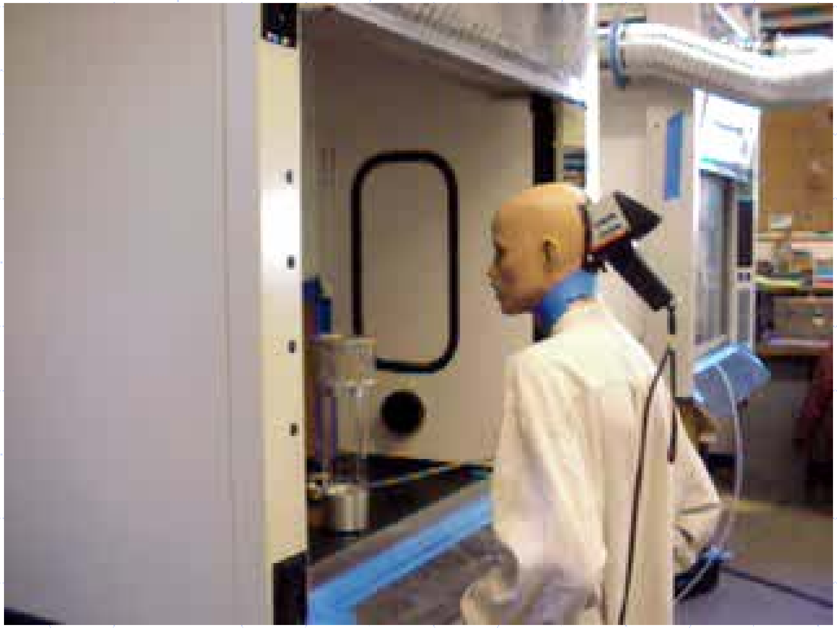
Prior cleanroom efficiency work

- Market assessment in CA
- Characterization of opportunity
- Design Charrettes/case studies
- Energy Benchmarking
- Cleanroom Programming Guide
- Research "Roadmap" for CA Energy Commission



Prior laboratory efficiency work

- Invention and development of high performance fume hood
- Laboratory design guide
- Design Intent Tool
- Laboratories for the 21st Century
  - Energy benchmarking
  - Design assistance
  - Training



Current laboratory activities

- Side-by-side testing of LBNL's high performance fume hood
- CAL/OSHA approval
- Industrial demonstrations
- Labs 21 participation including benchmarking

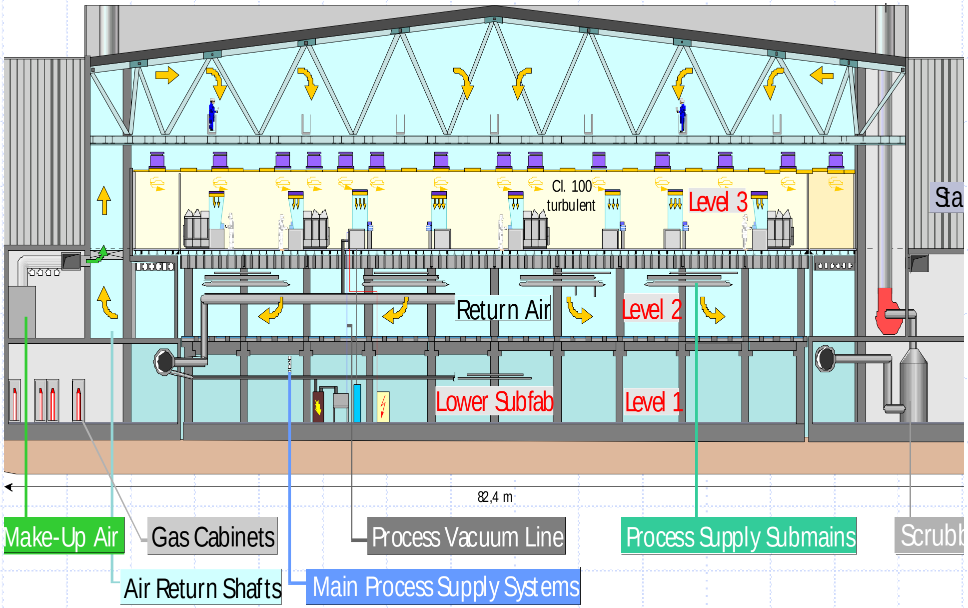
Business case - air system optimization

- Business case for energy efficiency in cleanroom air systems - saving energy puts $$ directly to bottom line
- Optimizing airflow may improve:
  - Production (yields)
  - Research results
  - Regulatory oversight
  - Maintenance frequency
  - And may *<u>Lower</u>* capital cost
- Some improvements are low or no cost

Types of Cleanrooms

- Each cleanroom is unique – but there are common efficiency opportunities
- Many industries and institutions use cleanrooms for a variety of processes
- Many different contamination control schemes
- Many different air systems designs

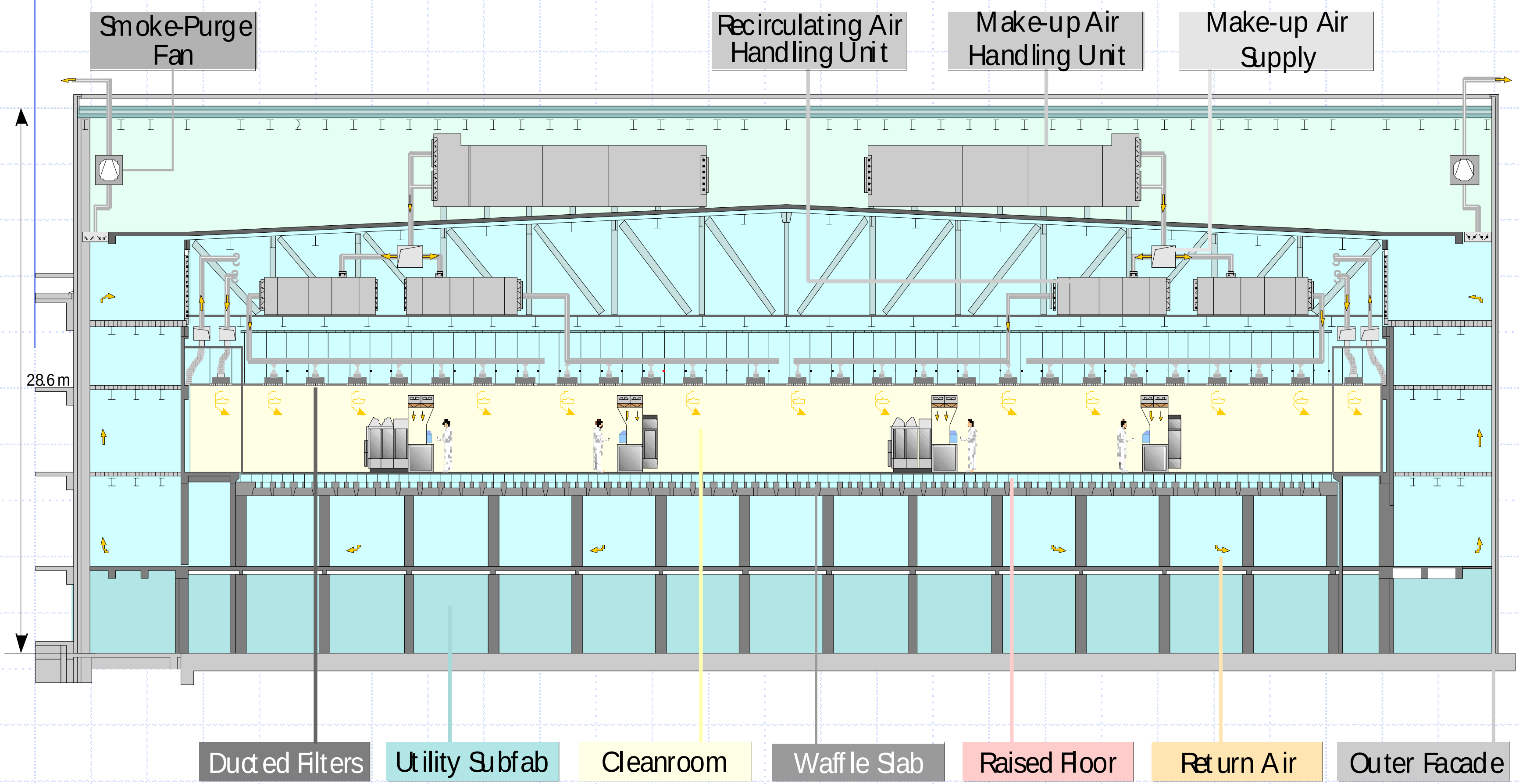
Cleanroom Arrangements



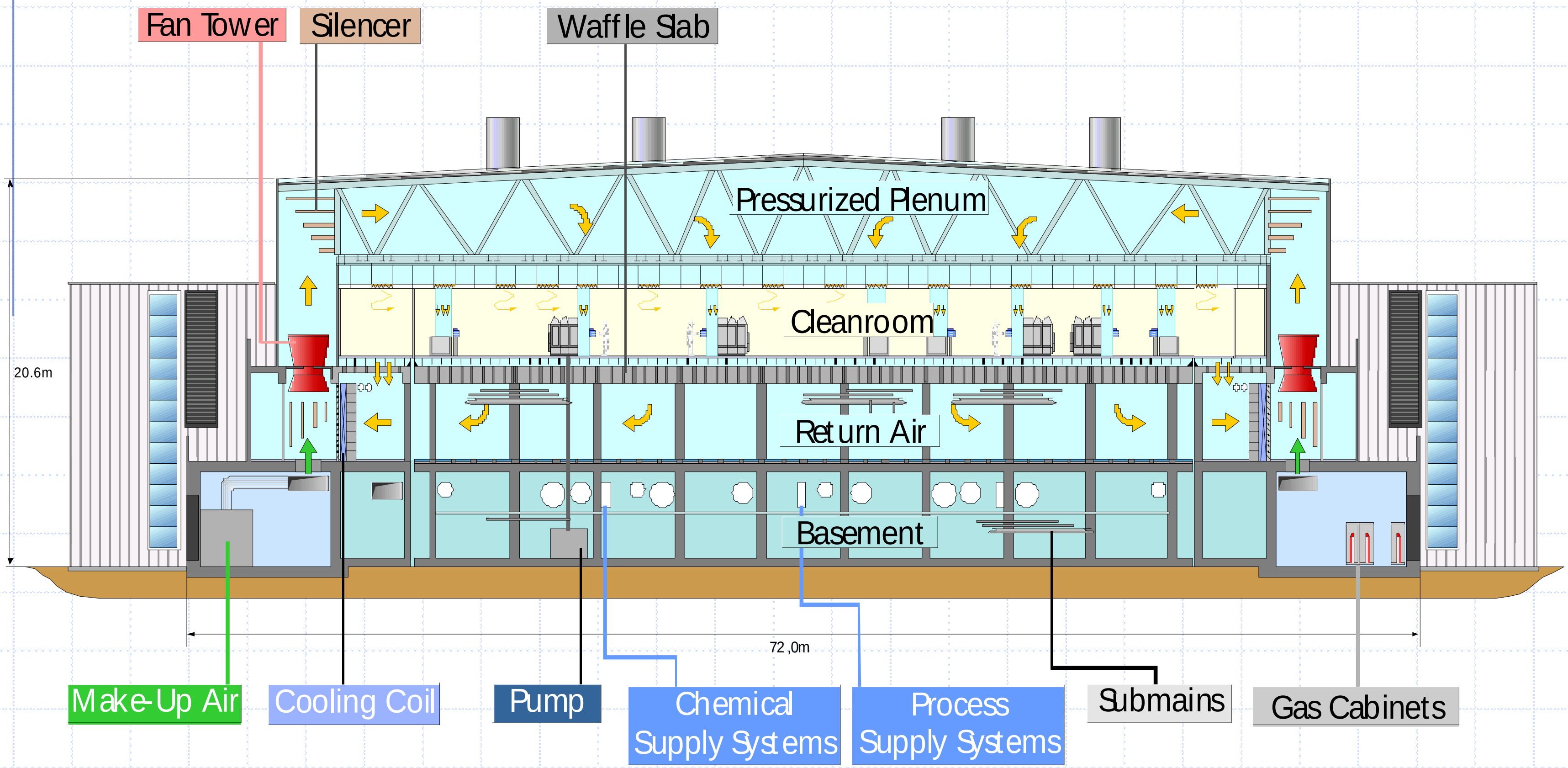
- Air Recirculation Concepts
- Building Concepts

Dr. Manfred Renz, Anto Filipovic, Stuttgart, Feb 2000

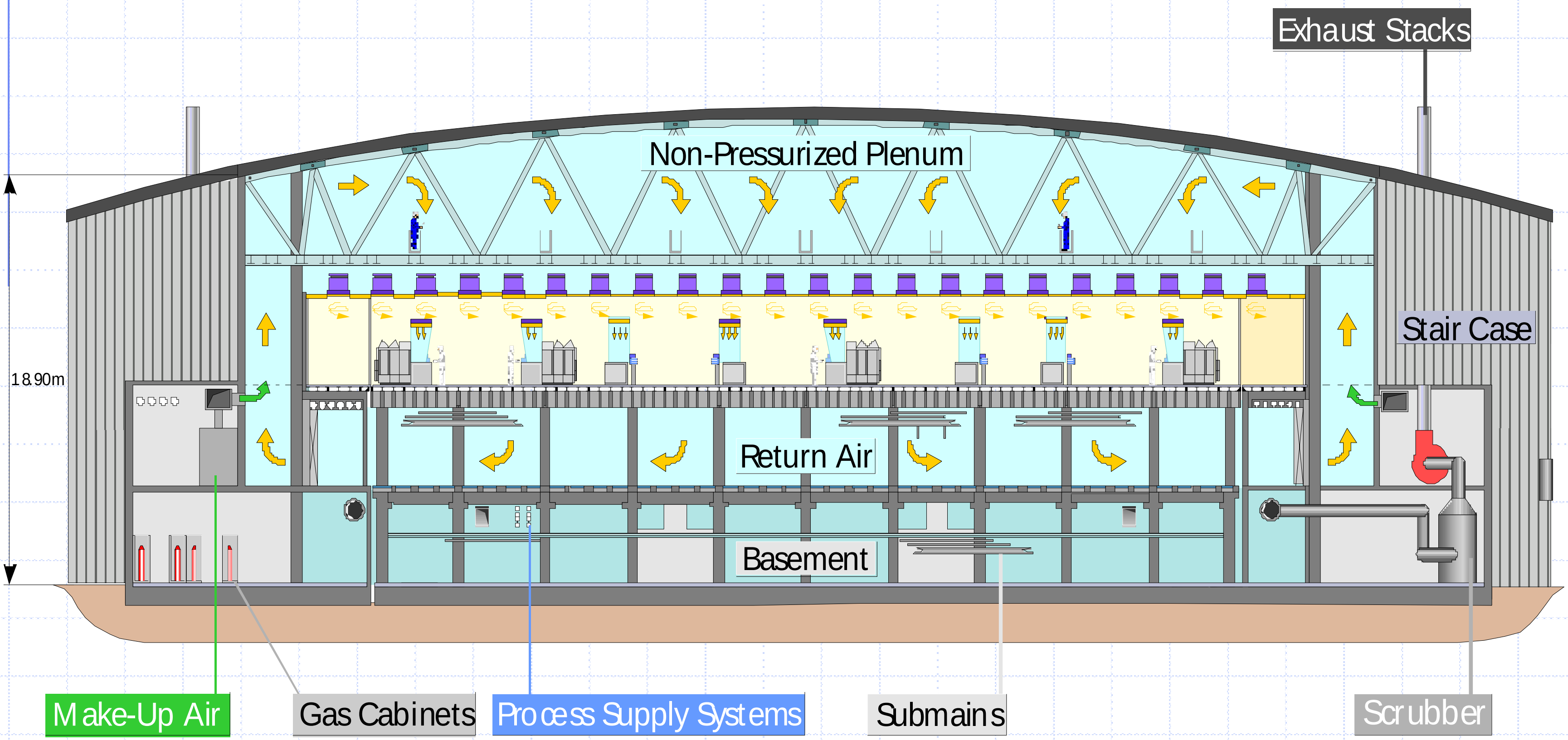
Recirculation concept 1: Recirculation units / ducted HEPA's



Recirculation concept 2: fan towers/ pressurized plenum



Recirculation air concept 3: fan-filter units



Another fan-filter scheme

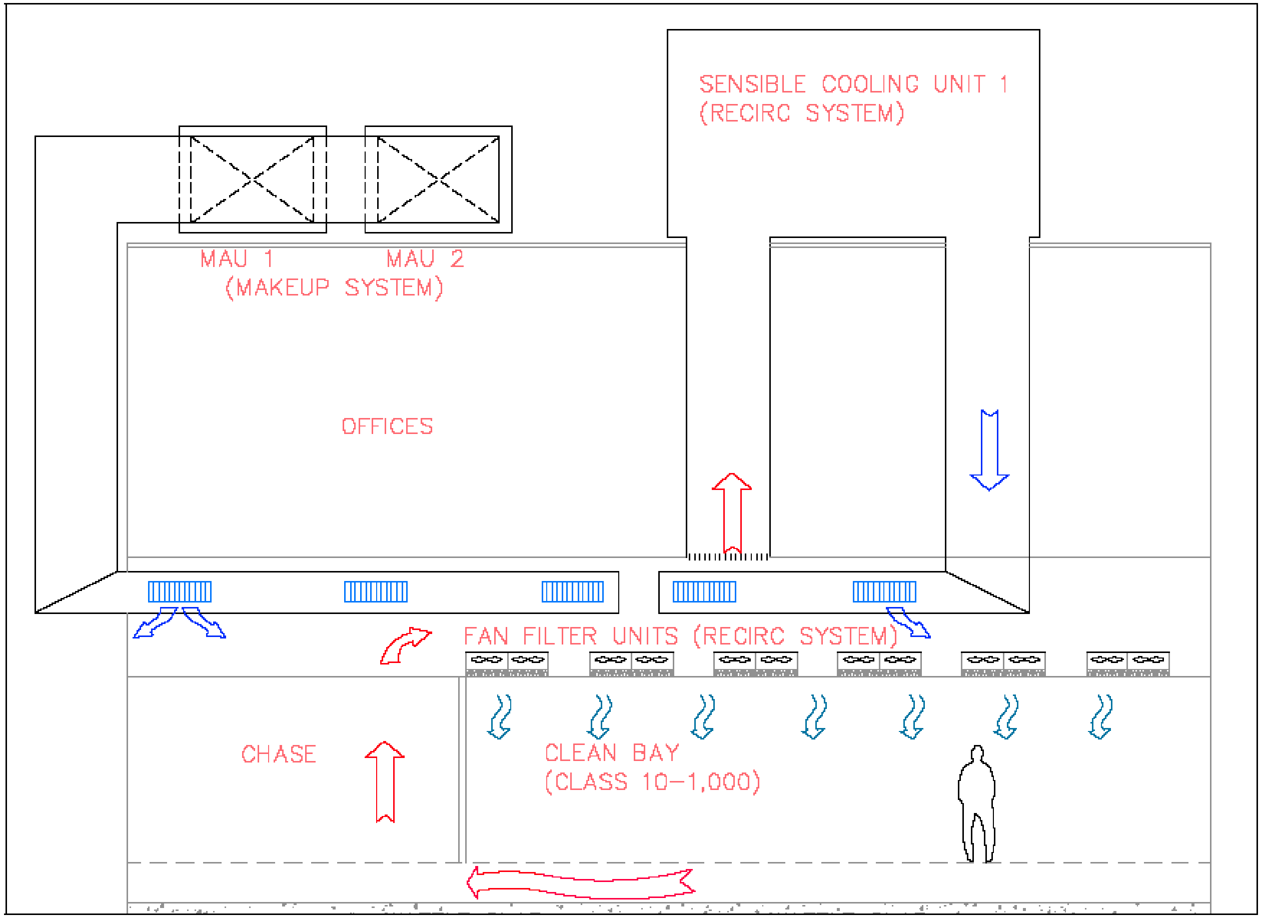


Figure: A Typical Fan Filter Unit Recirculation Air System and Makeup System

Resources

- ISO standards
- IEST recommended practices
- Cleanroom Design, second ed., W. Whyte
- LBNL
  - Cleanroom Programming Guide
  - Case Studies
  - Benchmark results
  - Design Intent tool
  - Laboratory Design Guide

Cleanliness standards

The Institute of Environmental Sciences and Technology (IEST) is developing a series of ISO standards that among other things replace Federal Standard 209E:

- ISO 14644 (1 through 8) – Cleanrooms and Controlled Environments
- ISO 14698 (1 through 3) - Biocontamination

The International Organization for Standardization (ISO)

ISO Standard 14644:

- Part 1: Classification of air cleanliness
- Part 2: Specifications for testing and monitoring to prove continued compliance with ISO 14644-1
- Part 3: Metrology and test methods
- Part 4: Design, construction and start-up
- Part 5: Operations
- Part 6: Terms and definitions
- Part 7: Separative devices
- Part 8: Classification of airborne molecular contamination

Biocontamination standards

- ISO 14698-1 General principles and methods.
- ISO 14698-2 Evaluation and interpretation of biocontamination data (pending).
- ISO 14698-3 Technical Report.

Cleanliness classes

Table 1 — Selected airborne particulate cleanliness classes for cleanrooms and clean zones

ISO classification number (*N*)	Maximum concentration limits (particles/m³ of air) for particles equal to and larger than the considered sizes shown below (concentration limits are calculated in accordance with equation (1) in 3.2)					
	0,1 µm	0,2 µm	0,3 µm	0,5 µm	1 µm	5 µm
ISO Class 1	10	2				
ISO Class 2	100	24	10	4		
ISO Class 3	1 000	237	102	35	8	
ISO Class 4	10 000	2 370	1 020	352	83	
ISO Class 5	100 000	23 700	10 200	3 520	832	29
ISO Class 6	1 000 000	237 000	102 000	35 200	8 320	293
ISO Class 7				352 000	83 200	2 930
ISO Class 8				3 520 000	832 000	29 300
ISO Class 9				35 200 000	8 320 000	293 000
NOTE Uncertainties related to the measurement process require that concentration data with no more than three significant figures be used in determining the classification level						

ISO 14644-1 cleanliness classes

ISO 14644-1 formula for maximum allowable particles

Airborne particulate cleanliness shall be designated by a classification number, N. The maximum permitted concentration of particles, C_n, for each considered particle size, D, is determined from the equation:

$$C_n = 10^N \times \left(\frac{0,1}{D} \right)^{2,08} \qquad (1)$$

where

- C_n is the maximum permitted concentration (in particles per cubic metre of air) of airborne particles that are equal to or larger than the considered particle size. C_n is rounded to the nearest whole number, using no more than three significant figures.
- N is the ISO classification number, which shall not exceed a value of 9. Intermediate ISO classification numbers may be specified, with 0,1 the smallest permitted increment of N.
- D is the considered particle size, in micrometres.
- 0,1 is a constant, with a dimension of micrometres.

Which class do I choose?

- Cleanliness class must match the contamination control problem
- Higher class than needed does not improve yield
- Cleanliness class and cleanroom protocol work together
- Higher class means more energy use (air changes/filtration/etc.)
- Facility staff and process engineers must work together to define

ISO 14644-4

Annex F
(informative)

Environmental control of cleanrooms

F.5 Energy conservation

Consideration may be given to incorporating in the design energy conservation considerations, such as provisions to reduce or close down temperature and humidity control and to reduce airflow during periods in which there is no activity. The ability to recover operating conditions in a defined recovery period should be demonstrated.

ISO 14644-4

Annex G
(informative)

Control of air cleanliness

G.4 Energy conservation

For energy conservation reasons, airflow of the ventilation systems may be reduced to low levels during non-operating periods. If, however, they are turned off, the potential for unacceptable room contamination to occur should be considered.

(Its OK to save energy!)

ISO 14644-4

Annex B
(informative)

Classification examples

Table B.1 — Cleanroom examples for aseptic processing of healthcare products

Air cleanliness class (ISO Class) in operation [a]	Airflow type[b]	Average, airflow velocity[c] m/s	Examples of applications
5 (at ⩾ 0,5 µm)	U	> 0,2	Aseptic processing[d]
7 (at ⩾ 0,5 µm)	N or M	na	Other processing zones directly supporting aseptic processing
8 (at ⩾ 0,5 µm)	N or M	na	Support zones of aseptic processing, including controlled preparation zones

NOTE 1 Application-specific classification requirements should take into account other relevant regulations.

NOTE 2 na = not applicable

[a] Occupancy states associated with the ISO Class should be defined and agreed in advance of establishing optimum design conditions.

[b] When airflow type is listed, it represents the airflow characteristics for cleanrooms of that class: U = unidirectional; N = non-unidirectional; M = mixed (combination of U and N).

[c] Average airflow velocity is the way that unidirectional airflow in cleanrooms is usually specified. The requirement on unidirectional airflow velocity will depend on specific application factors such as temperature, and configuration of the controlled space and the items to be protected. Displacement airflow velocity should be typically above 0,2 m/s.

[d] Where operator protection is required to ensure safe handling of hazardous materials, the use of segregation concepts (see examples in annex A) or appropriate safety cabinets and devices should be considered.

Table B.2 — Examples for microelectronic cleanrooms

Air cleanliness class[a] (ISO Class) in operation	Airflow type[b]	Average, airflow velocity[c] m/s	Air changes per hour[d] $m^3/m^2 \cdot h$	Examples of applications
2	U	0,3 to 0,5	na	Photolithography, semiconductor processing zone[e]
3	U	0,3 to 0,5	na	Work zones, semiconductor processing zone
4	U	0,3 to 0,5	na	Work zones, multilayer masks processing, fabrication of compact discs, semiconductor service zone, utility zones
5	U	0,2 to 0,5	na	Work zones, multilayer masks processing, fabrication of compact discs, semiconductor service zone, utility zones
6	N or M[f]	na	70 to 160	Utility zones, multilayer processing, semiconductor service zones
7	N or M	na	30 to 70	Service zones, surface treatment
8	N or M	na	10 to 20	Service zones

NOTE na = not applicable

[a] Occupancy states associated with the ISO Class should be defined and agreed in advance of establishing optimum design conditions.

[b] When airflow type is listed, it represents the airflow characteristics for cleanrooms of that class: U = unidirectional; N = non-unidirectional; M = mixed (combination of U and N).

[c] Average airflow velocity is the way that unidirectional airflow in cleanrooms usually is specified. The requirement on unidirectional airflow velocity will depend on local parameters such as geometry and thermals. It is not necessarily the filter face velocity.

[d] Air changes per hour is the way that non-unidirectional and mixed airflow is specified. The suggested air changes are related to a room height of 3,0 meter.

[e] Impervious barrier techniques should be considered.

[f] With effective separation between contamination source and zones to be protected. Could be a physical or airflow barrier.

Cleanroom Programming Guide

- Provides general guidance on topics often decided during programming phase
- Facilitates agreement between owner and designer
- Reinforces that energy is an equally important consideration

Cleanroom Programming Guide

How does the guide relate to air systems design?

- Minimize clean space
- Correct cleanliness level
- Optimal air change rate
- Consider use of mini-environments
- Optimize ceiling coverage
- Consider cleanroom protocol and cleanliness class
- Minimize pressure drop (air flow resistance)
  - Location of large air handlers – close to end use
  - Adequate sizing and minimize length of ductwork
  - Provide adequate space for low pressure drop air flow
  - Low face velocity

Cleanroom Programming Guide

More concepts from the guide:

- Use of variable speed fans
- Optimizing pressurization
- Consider air flow reduction when unoccupied
- Efficient components
  - Face velocity
  - Fan design
  - Motor efficiency
  - HEPA filters ΔP
  - Fan-filter efficiency
  - Electrical systems that power air systems

Savings By Design

Cleanroom baseline criteria

Recirculation system

- Metric: Watts/cfm
- Determine watts by measurement or from design BHP

$$W = \frac{BHP \times 746}{0.91}$$

- Determine flow from balance report or design documents
- Baseline value is 0.43 W/cfm (2,325 cfm/kW)
- Annual savings=(Baseline - Efficiency metric) x Annual cfm

Savings By Design

Cleanroom baseline criteria

Make-up air system

- Metric: Watts/cfm
- Determine watts by measurement or from design BHP

  $$W = \frac{BHPx746}{0.91}$$

- Determine flow from balance report or design documents
- Baseline value is 1.04 W/cfm (961 cfm/kW)
- Annual savings=(Baseline - Efficiency metric) x Annual cfm

  where annual cfm = .7 x design cfm

- Run redundant stand-by units in parallel

Savings By Design

Cleanroom baseline criteria

Additional criteria for:

- Chilled water system
- Hot water production
- Compressed air

Savings By Design

Five largest energy savings opportunities:

- Low face velocity in air handlers
- Variable speed chillers
- Free cooling for process loads
- Dual temperature cooling loops
- Recirculation air setback

LBNL energy benchmarking

Prior Benchmarking Studies available at: http://ateam.lbl.gov/cleanroom/benchmarking/results.html

LBNL obtained energy benchmarks for fourteen cleanrooms. Energy end-use was determined along with energy efficiency of key systems.

Energy efficiency recommendations were provided to each facility.

Adding benchmarks

Additional energy benchmarks:

In the mid-ninety's Sematech benchmarked fourteen semiconductor cleanrooms around the world. Similar metrics were obtained although measurement techniques may have differed.

CA energy benchmarking

Currently:

Additional energy benchmarking is being performed in California with an emphasis on air systems .

Benchmarking sites are being sought –
4 to 6 cleanrooms.

Labs 21 is also collecting benchmarks.

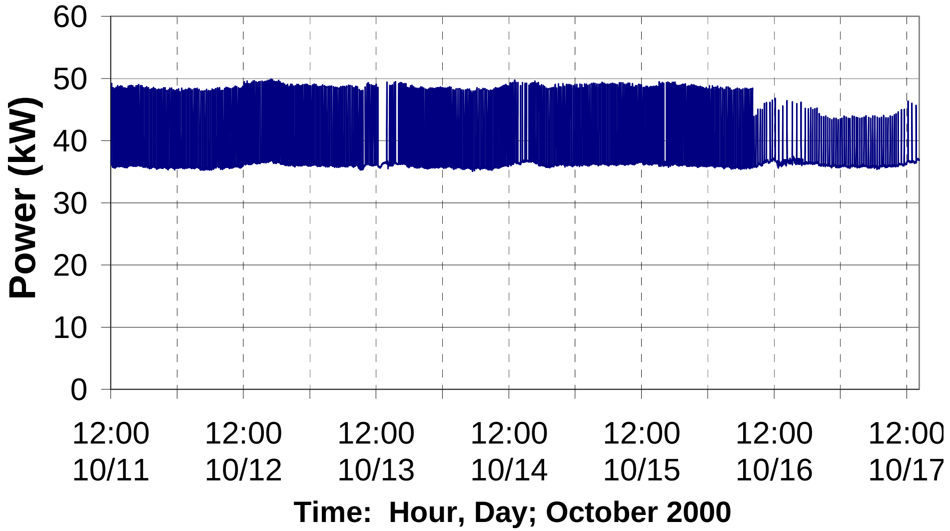
Benchmarking benefits

- Establish Baseline to Track Performance Over Time
- Prioritize Where to Apply Energy Efficiency Improvement Resources
- Identify Maintenance and Operational Problems
- Operational Cost Savings
- Identify Best Practices

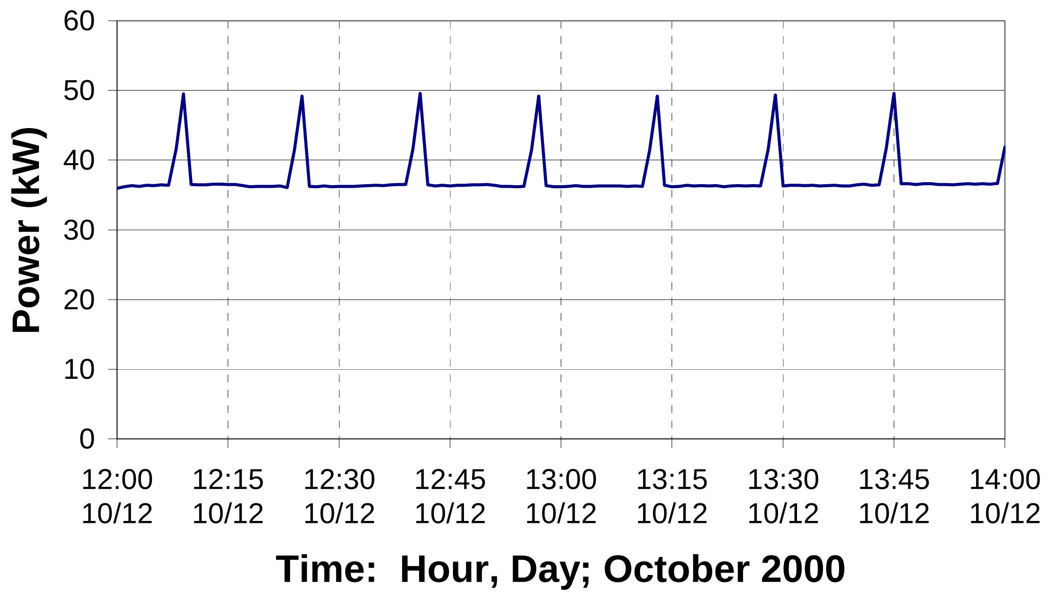
Plus non-energy benefits

- Reliability Improvement
  - Controls
  - Setpoints
- Maintenance identification
  - Leaks
  - Motors, pumps, Fans
  - Filters
  - Chillers, boilers, etc.
- Safety issues uncovered
  - Hazardous air flow

Chilled Water Pump Power



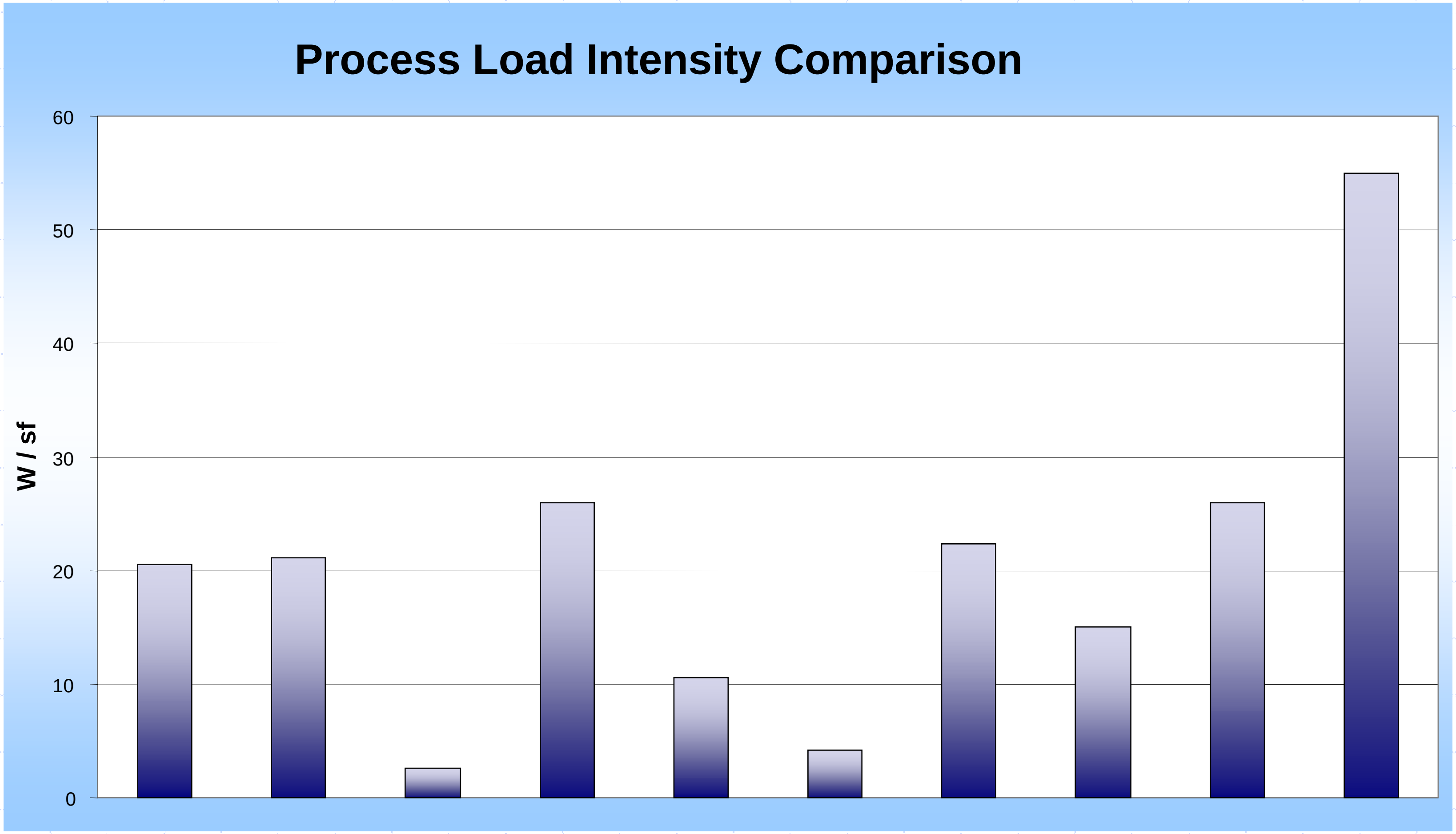
Chilled Water Pump Power



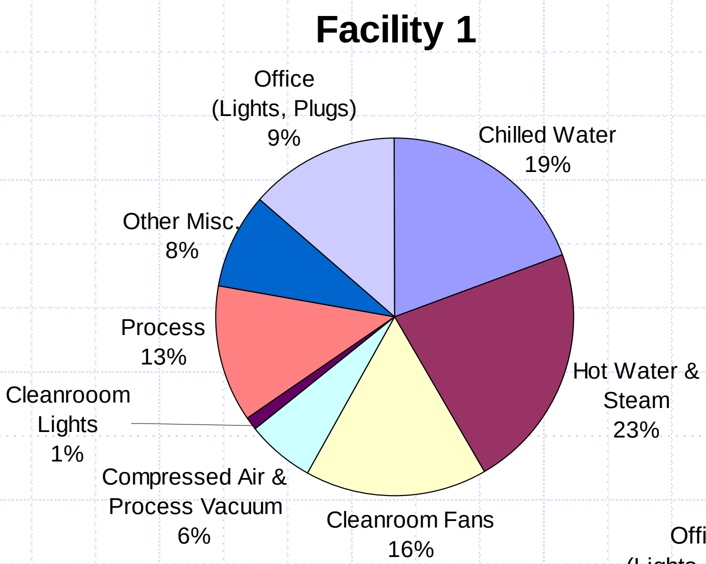
System efficiency vs. production efficiency

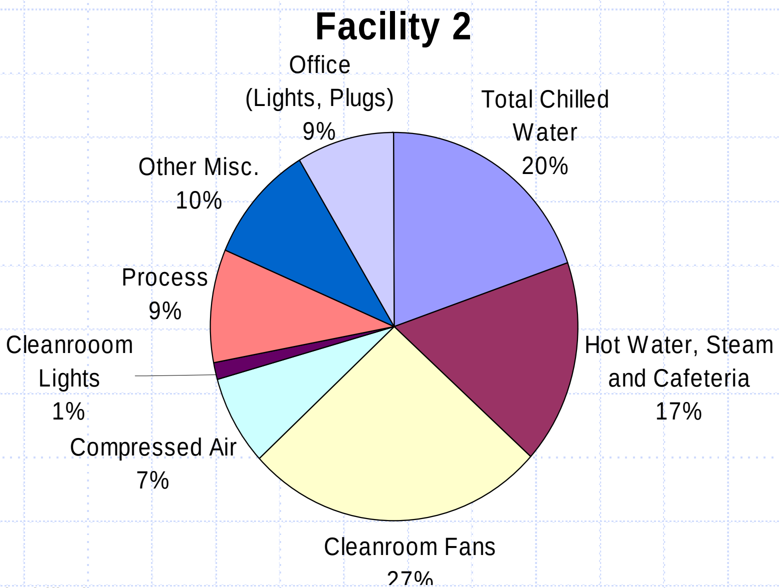
- Metrics allow comparison of air system efficiency regardless of process – e.g. cfm/kW or kW/cfm
- Production metrics can mask inefficient systems – e.g. kW/cm^2 (of silicon) or kW/lb of product

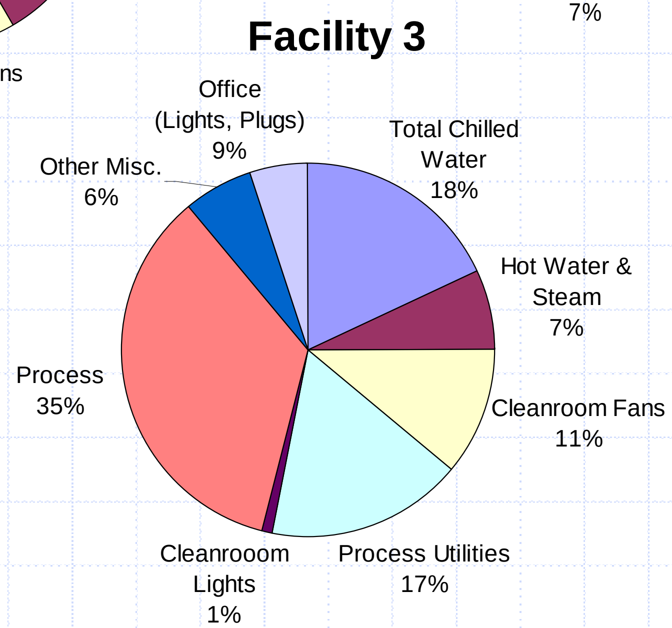
Process electrical load intensity (heat load)



Energy end-use







What are the costs?

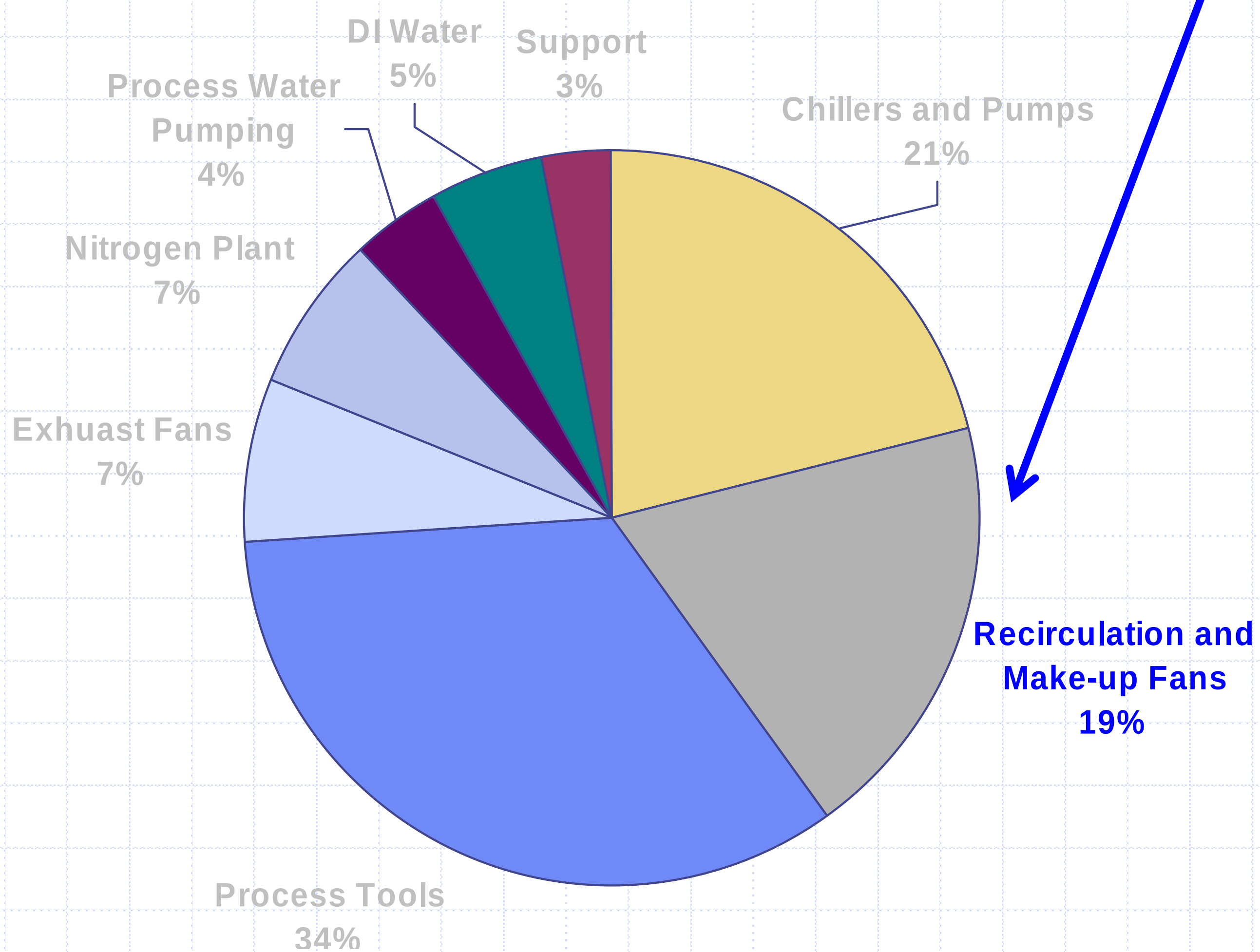
Utility bills from one case study:

Billing days		Dollars
Elec 368	38,084,148 kWh	$2,549,330
Gas 371	70,203 therms	$43,715

approx 20,000 sq ft cleanroom in 68,000 sq ft building w/ $.065 ave. per kW!

Energy intensive systems

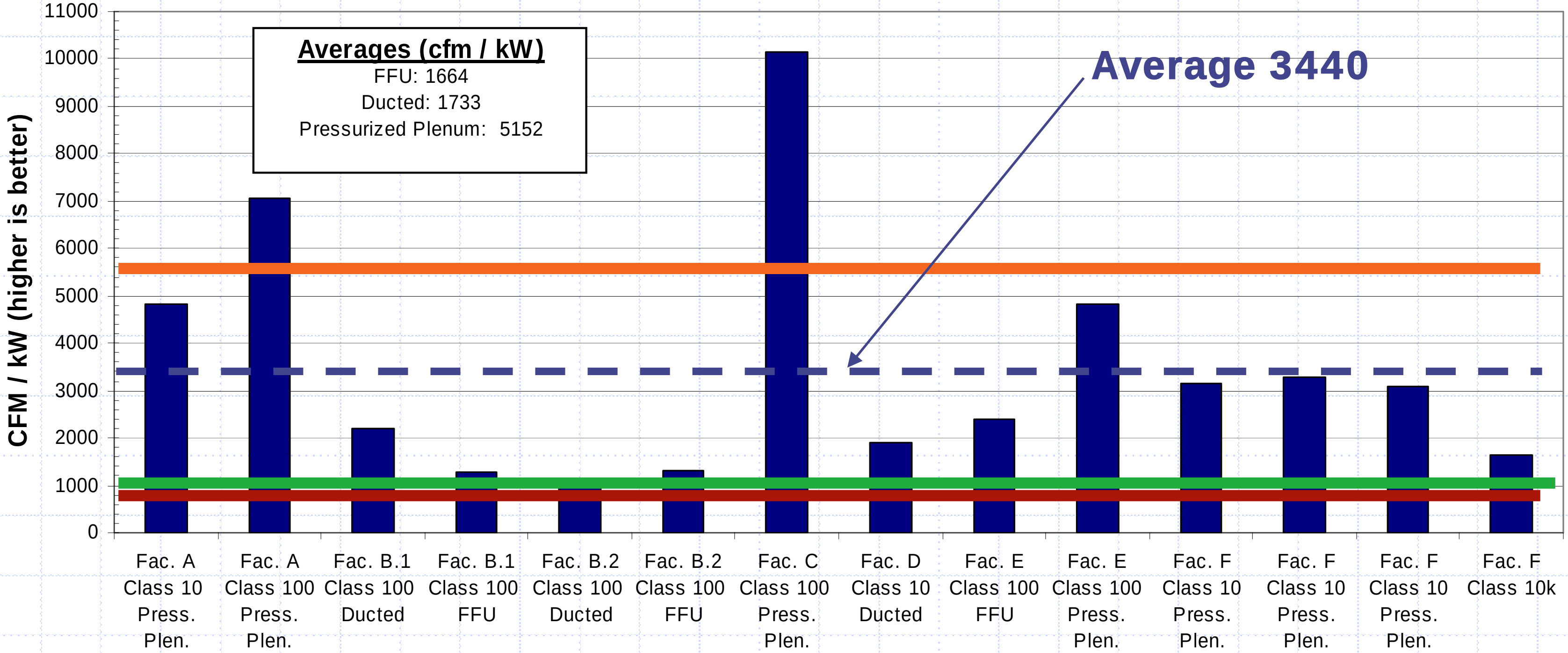
air systems in cleanrooms



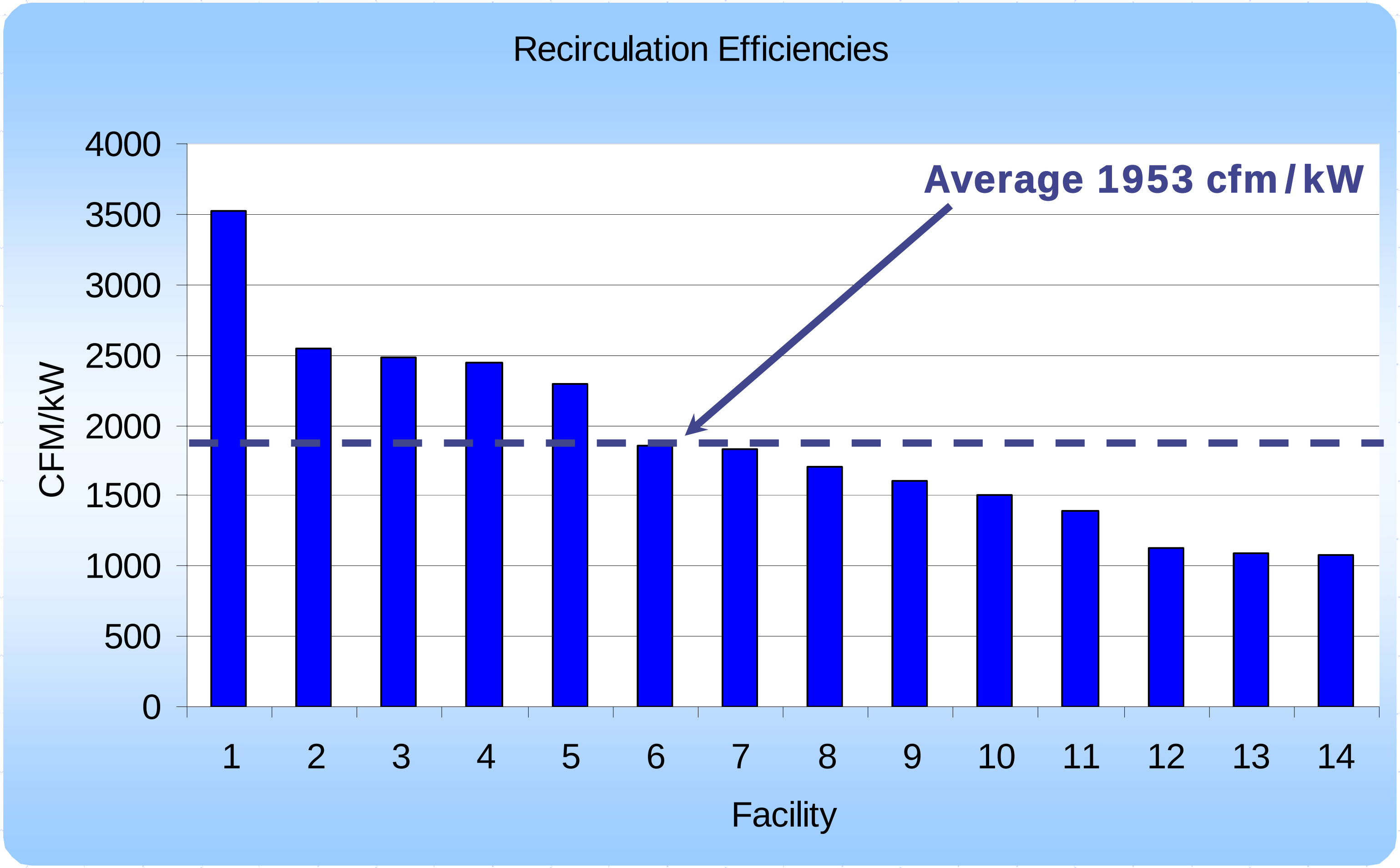
Cleanroom air system metrics

- Air systems – cfm/kW
  - Recirculation
  - Make-up
  - Exhaust
- Cleanroom air changes – ACH/hr
  - Recirculated, filtered air
  - Outside air (Make-up and Exhaust)
- Average room air velocity - ft/sec

Recirculation air comparison



Recirculation efficiency – Sematech study



Using benchmarks to set goals

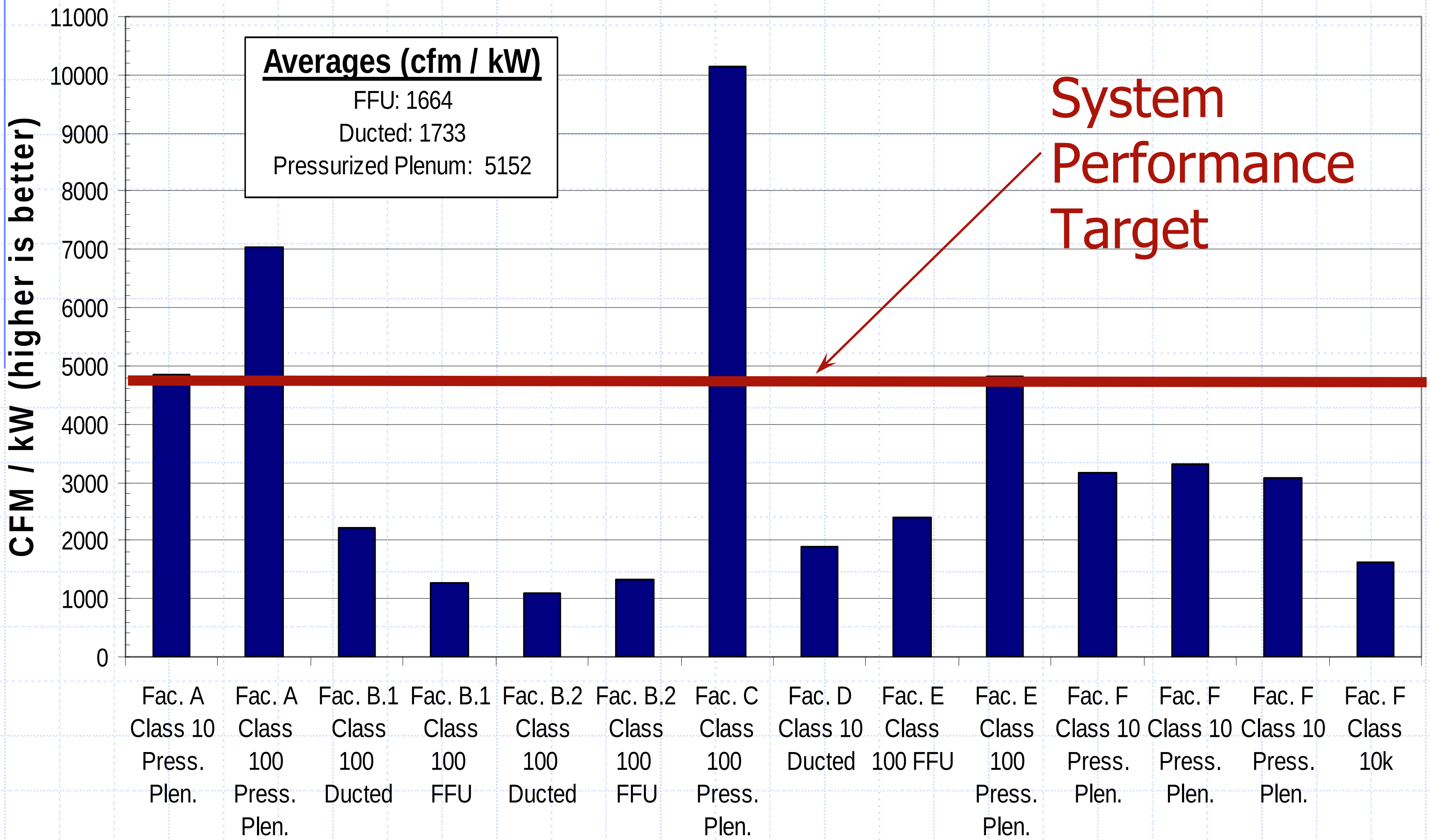
Building Owners and Designers can use benchmark data to set energy efficiency goals.

Goal setting and benchmarking

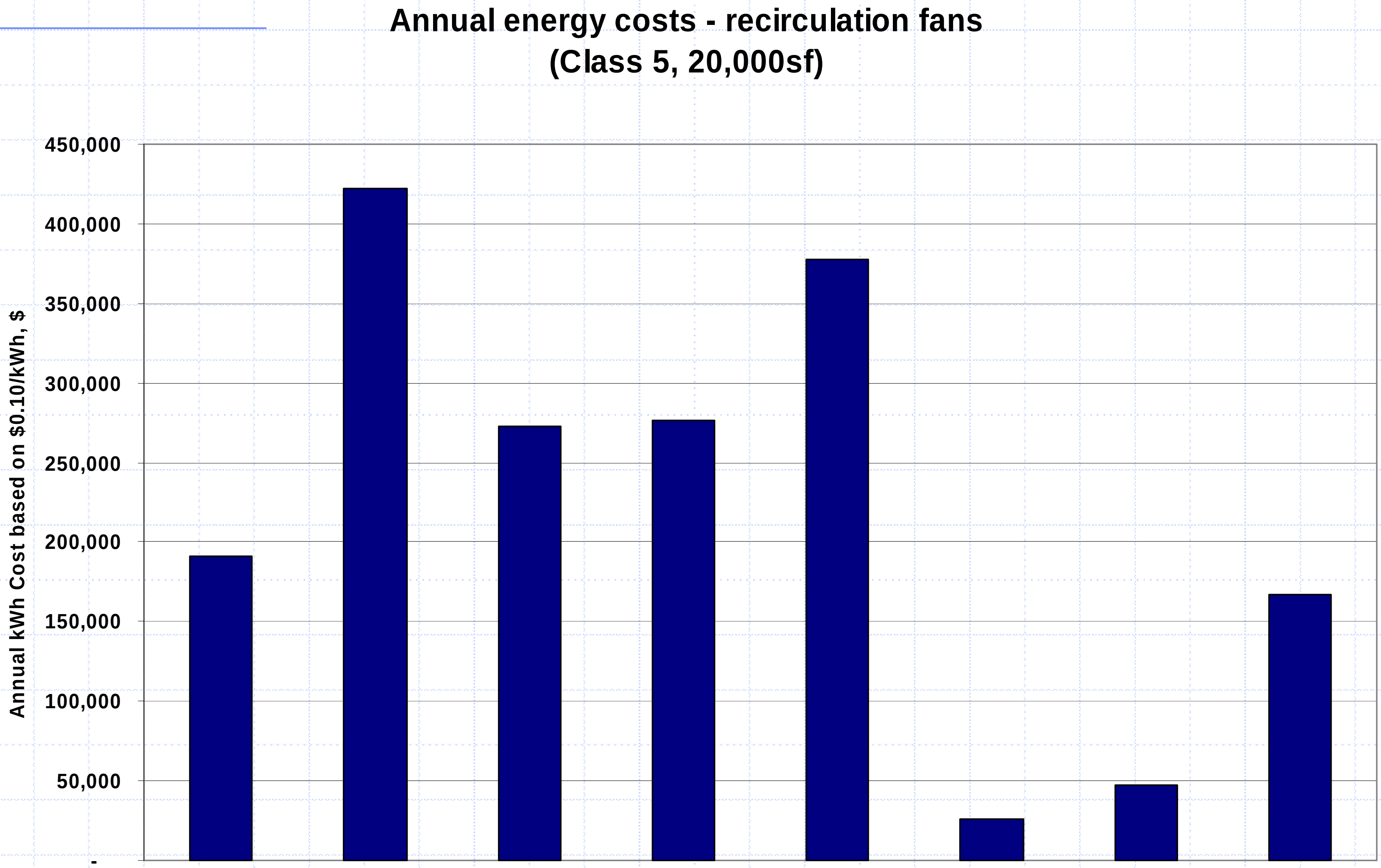
- Facility and End Use “Energy Budgets”

- Efficiency Targets or Design Requirements for Key Systems and Components
  - **Cfm / KW**
  - **KW / ton**
  - **System resistance – i.e. Pressure drop**
  - **Face velocities**
  - **Etc.**

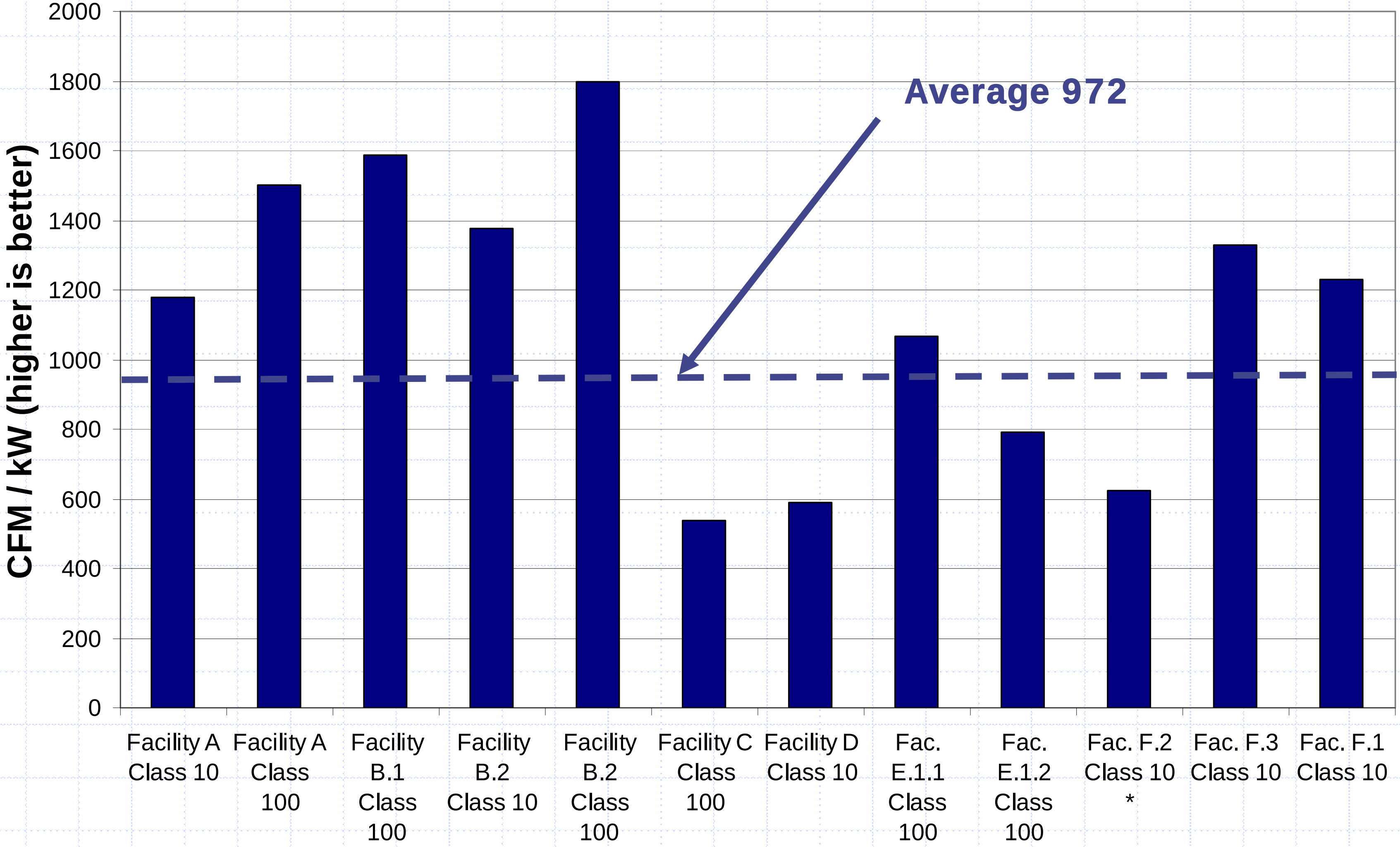
Recirculation air comparison



Hypothetical operating cost comparison

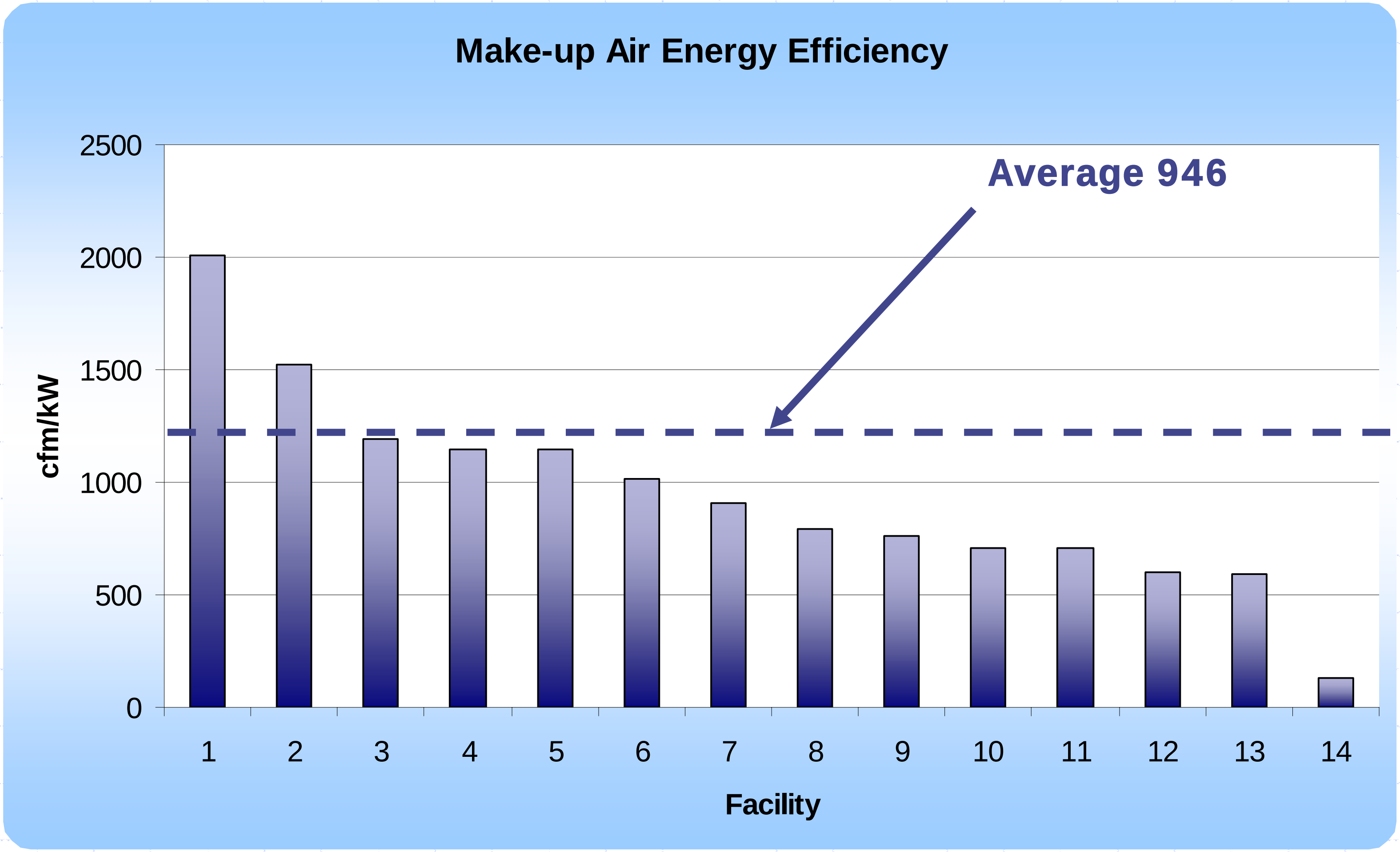


Make-up system comparison



Make-up system efficiency

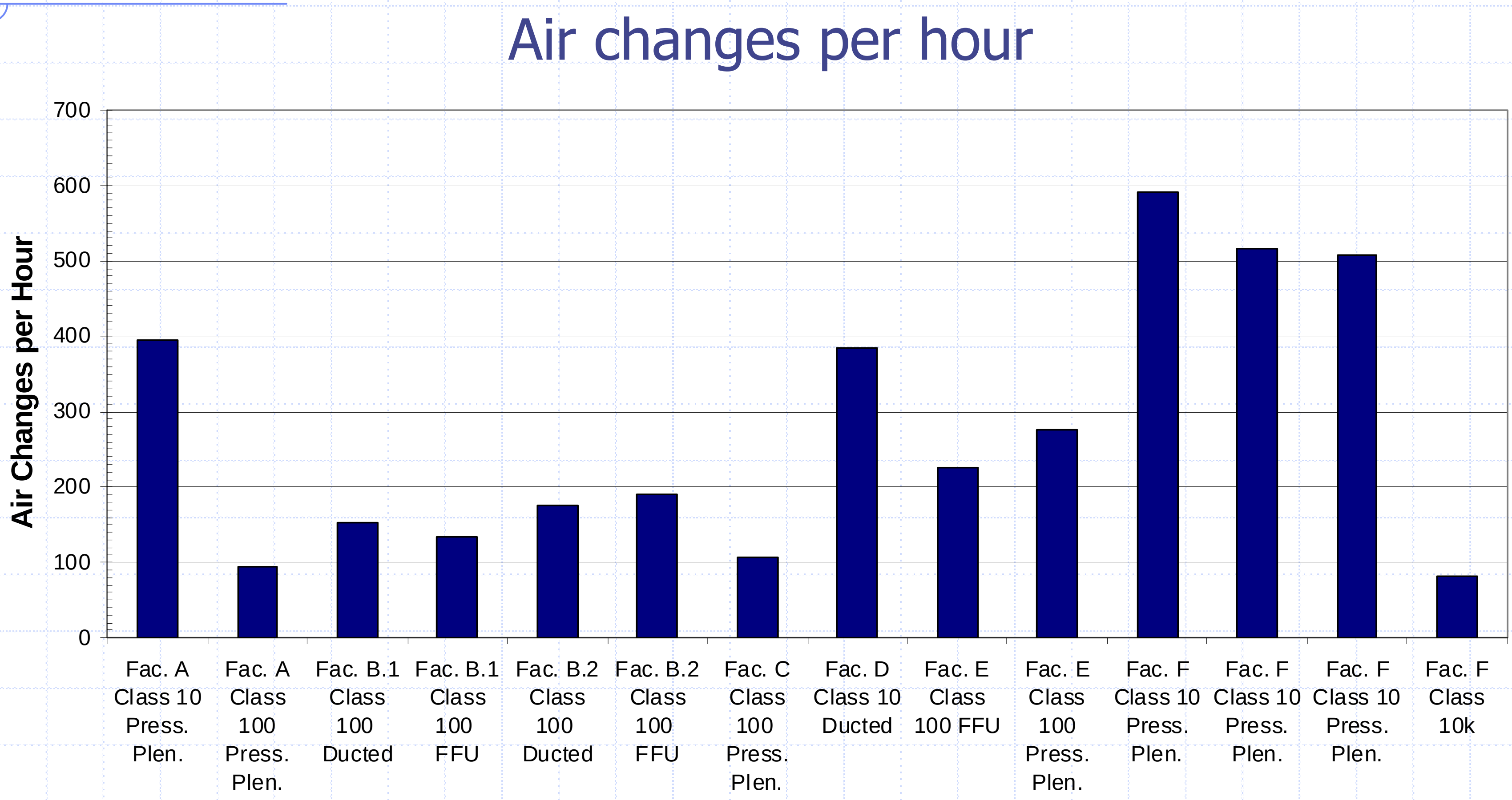
Sematech study



Make-up system efficiency

- Adjacency of air handler(s) to cleanroom
- Resistance of make-up air path
- Pressurization/losses/exhaust
- Air handler face velocity
- Coil Pressure Drop
- Duct/plenum sizing and layout
- Fan and motor efficiency
- Variable Speed Fans

Recirculated air system



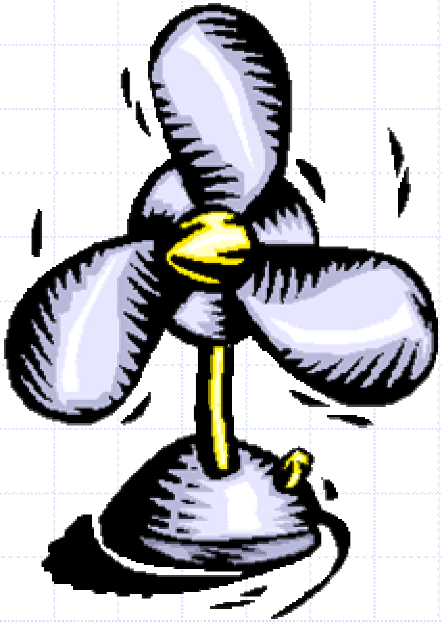
Cleanroom benchmarking highlights some important issues

- Contamination control can often be achieved with reduced air change rates
- Cleanliness ratings are often higher than needed
- Criteria based upon rules of thumb should be examined (90ft/min, air changes, etc.)
- Overcooling and subsequent reheat can be excessive
- Many owners don’t know how they compare

Air-change and velocity choices

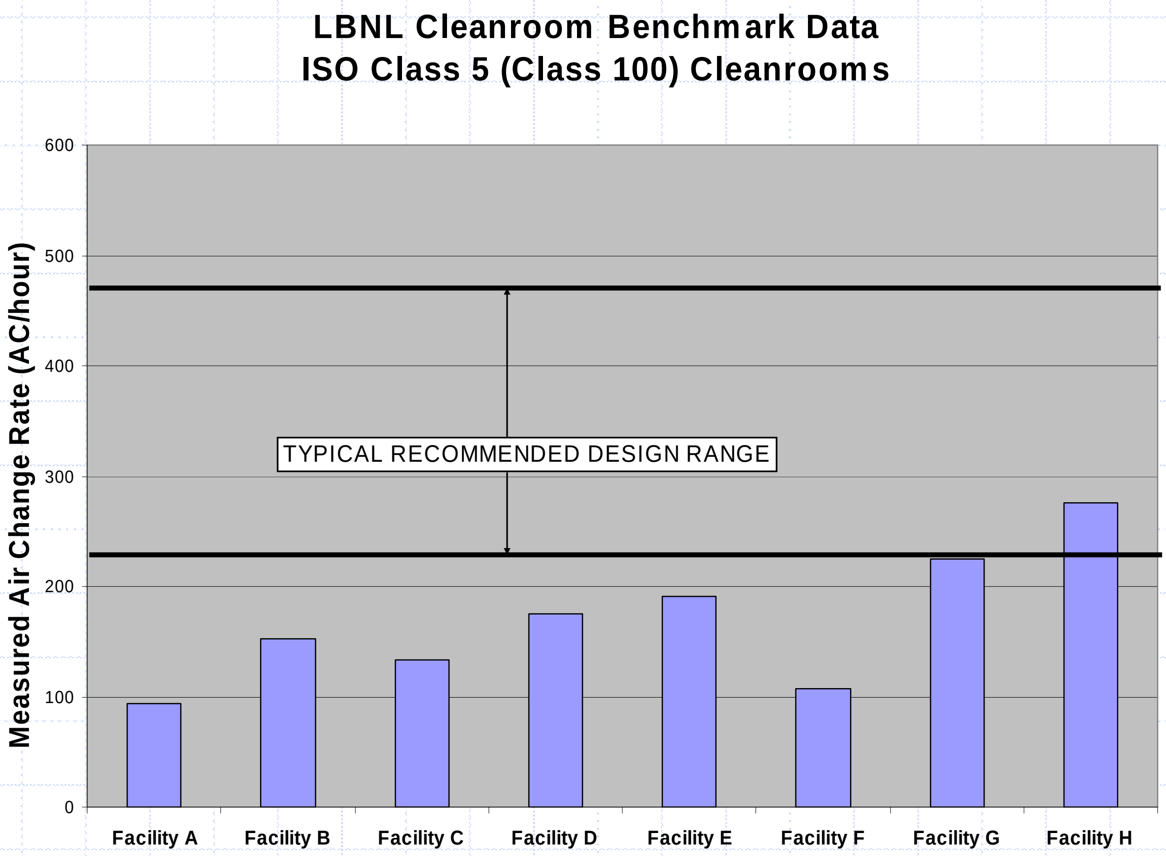
Not an exact science…

- IEST provides recommended recirculation air-change rates
- Variable speed fans (start low with ability to increase)
- Ceiling coverage
- Pressurization/losses
- Cleanroom protocol



Recirculated air change rates

ISO class 5



Recommended ranges from Cleanroom Design, second ed., W. Whyte

Make-up/exhaust air-change rates

- Make-up and exhaust air-change rates were not benchmarked
- Typically driven by code and process requirements and so are industry/process specific
- Process exhaust optimization (and resulting decrease in conditioned make-up air) is an opportunity in many cleanrooms
- Personnel safety is no. 1 but there is room to optimize

Ceiling filter coverage

Also not an exact science…

ISO class 1-4	100%
ISO class 5	75-100%
ISO class 6	30-50%
ISO class 7	15-20%
ISO class 8	5-10%

Within the system…

Efficiency choices can be made in many areas

- System pressure drop – face velocity, duct velocity, chases, plenums, adjacency, layout
- Air change rates
- Ceiling coverage
- Equipment – fans, motors, controls, filters, floor systems

Flow visualization

CFD Models and other visualization techniques can help solve problems

Fan-filter unit selection

How does one select an energy efficient fan-filter unit?

A. Rely on sales representative recommendation
B. Use published manufacturers data
C. Recommendation from peers
D. Use your company's standard

E. None of the above

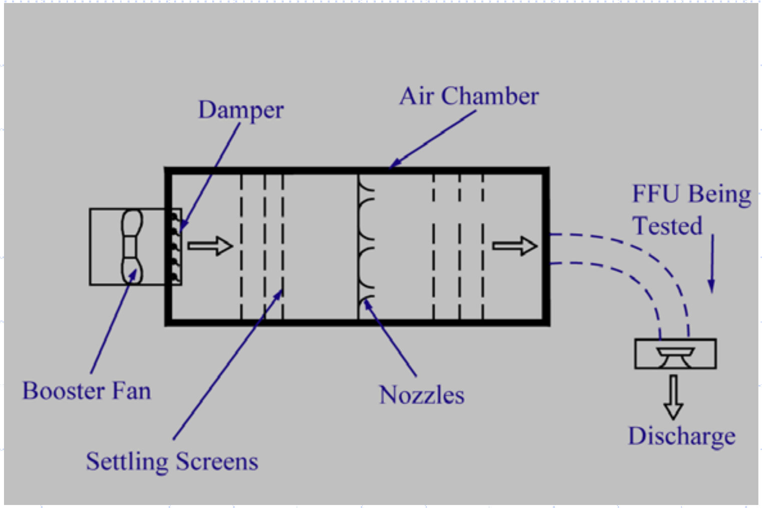
Fan-filter unit selection

None of the above

- Manufacturers report performance in various ways for various operating conditions – no apples to apples comparison
- A standard method of testing and reporting is being developed through LBNL and IEST
- For now, either specify that performance should be documented in accordance with the draft procedure, or specify your conditions and request bid information in a consistent manner.
- Utilities are interested in developing incentive baselines.

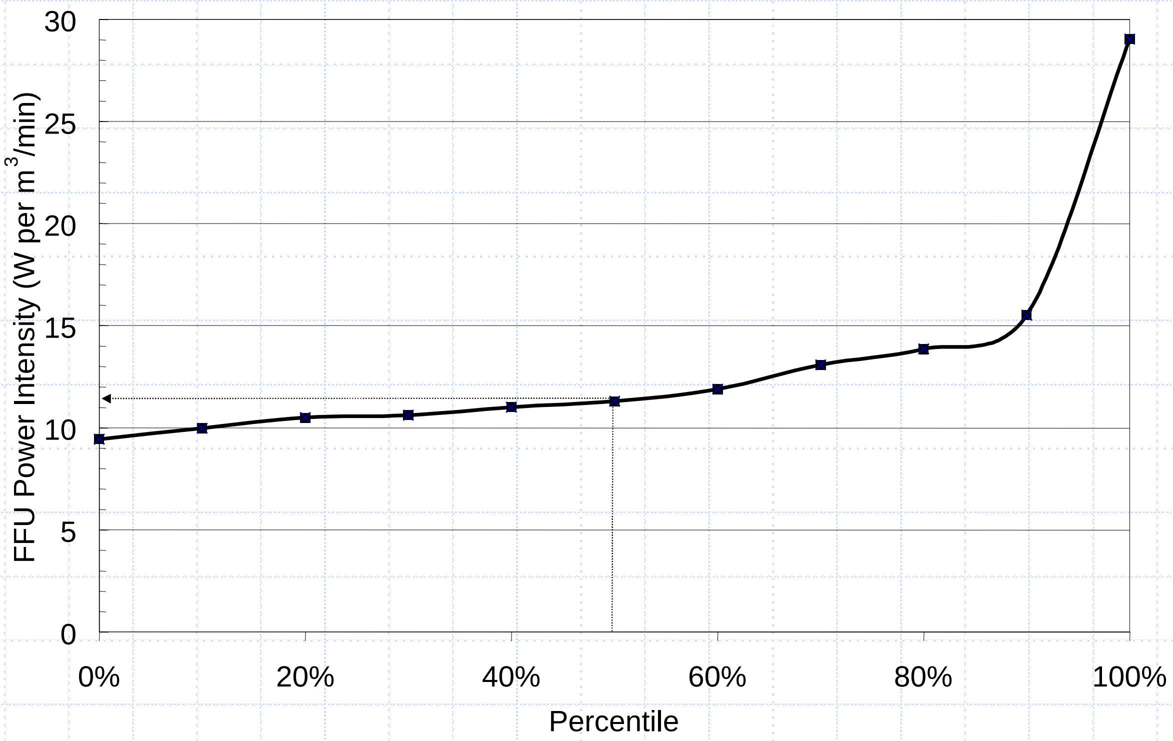
Fan-filter unit selection

Standardized testing will allow apples to apples comparison

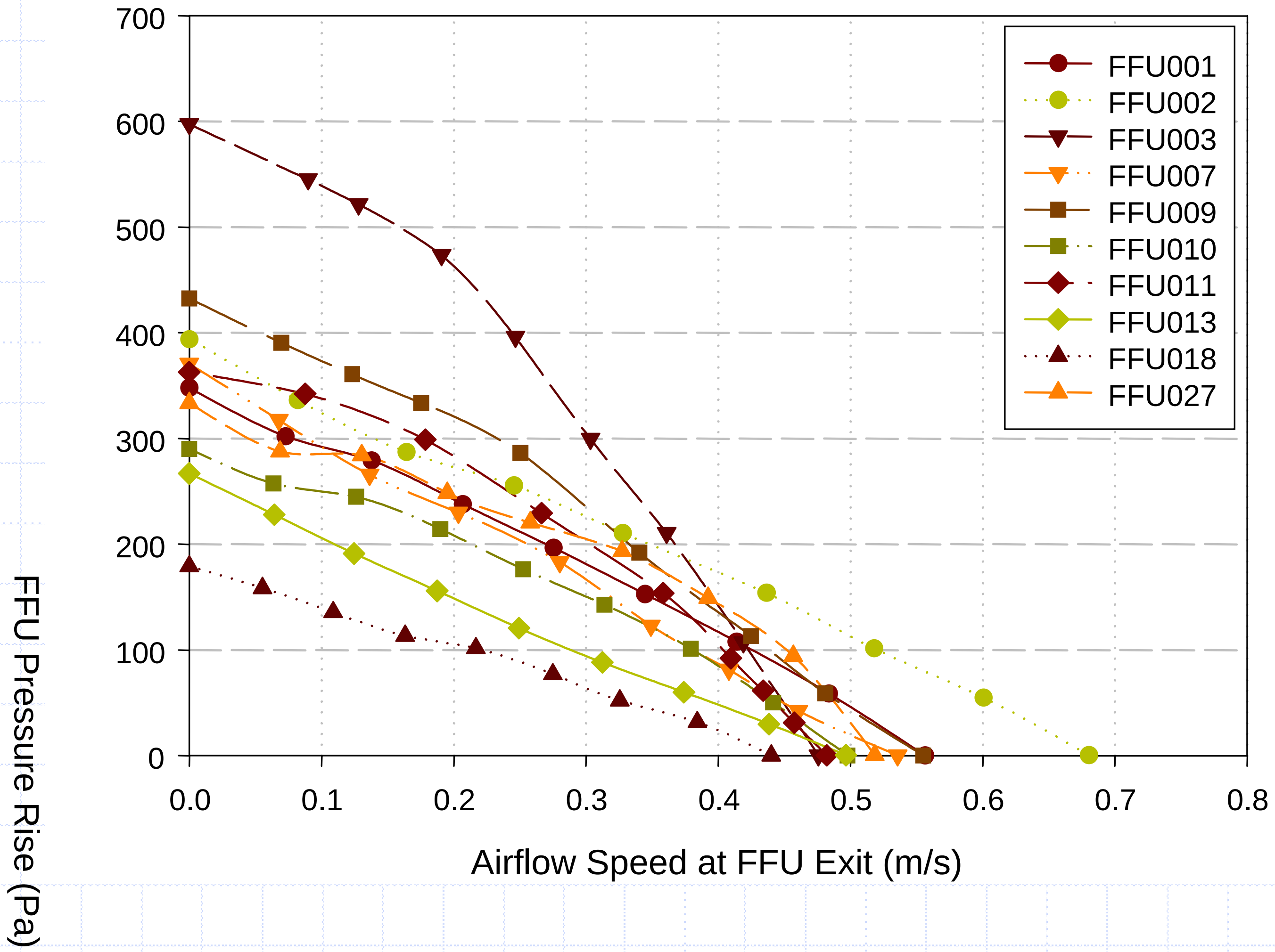


Energy performance index

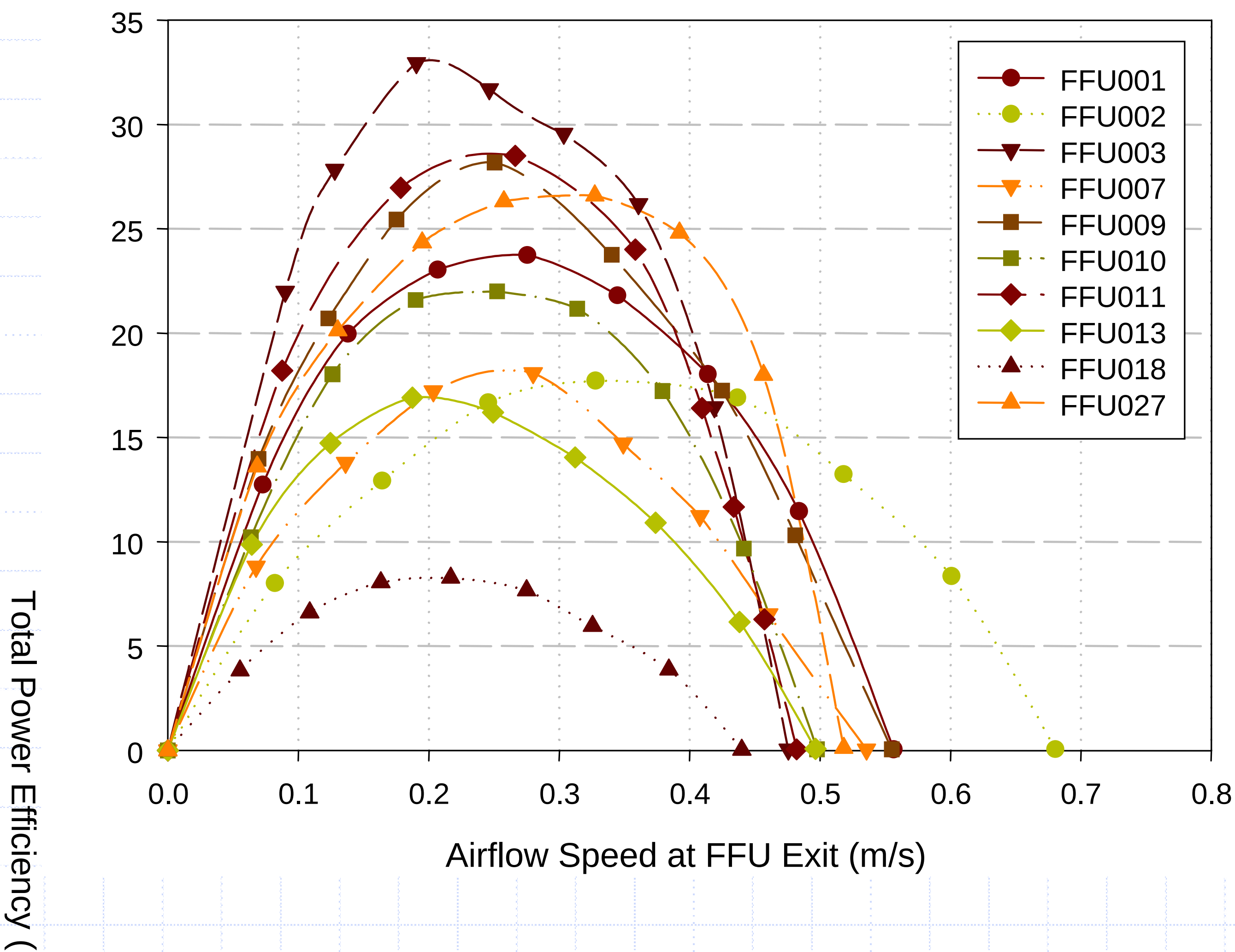
(for a given airflow rate)



Pressure vs. airflow speed

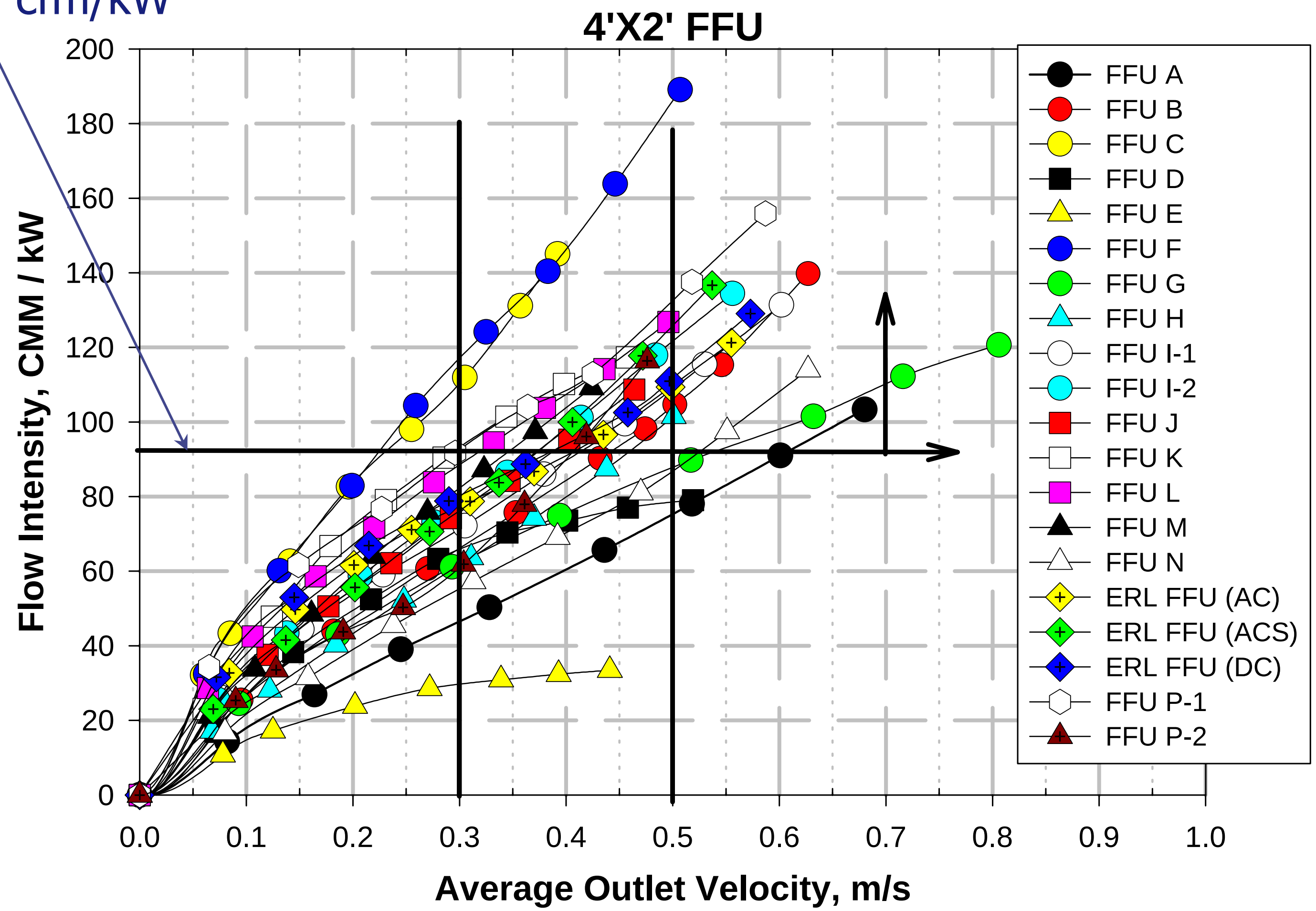


Total power efficiency



Flow / kW comparison

2800 cfm/kW



Source: Industrial Technology Research Institute, Taiwan

Case study

Good news/Bad news

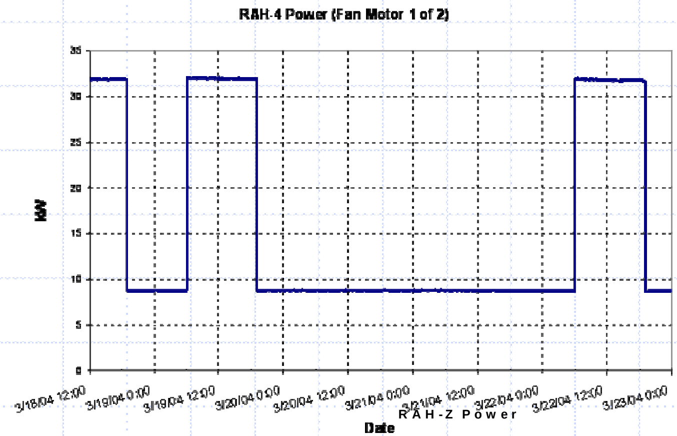
A night time recirculation setback was successfully utilized and dramatically saved energy

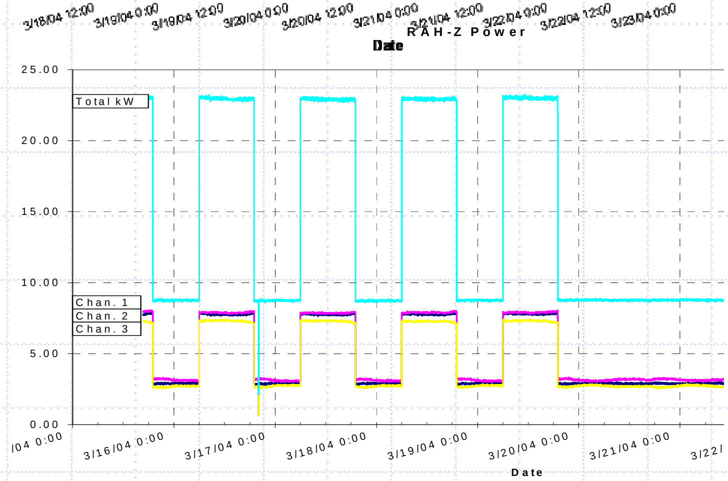
Unfortunately air change rates were very high and a ducted system was used

Ducted HEPA's create more pressure drop

Case study – recirculation setback

- Based Solely on Timeclock, 8:00 PM - 6:00 AM setback
- No reported process problems or pushback
- 60% – 70% Power Reduction on turndown





Case study – recirculation setback

- Annual fan savings from daily and weekend setback:

  1,250,000 kWh
  approximately $138,000

- Cooling load reduction when setback:

  234 kW
  65 tons

Case study - recommendation

- Air change rates exceeded IEST recommendations during daylight operation
- Further large reductions in energy use are possible by reducing air change rates and should not affect the process occurring in the room

Best practices/conclusions

Sizing of air systems:

- Minimize clean space
- Correct classification for contamination problem
- Air change rate
- Minimize pressure drop
- VFD's can help
- Exhaust minimization

Best practices observed

Factors affecting air flow resistance

- duct size (oversized is good)
- low face velocity
- minimize length of duct/air path
- efficient, low pressure drop filters
- raised floor air resistance (% open)
- size and placement of return air chases
- Use of plenums

Integrated approach

For new and retrofit construction, integration of Mechanical, Electrical, and Architectural disciplines is critical. Examples:

- Sizing systems for real loads (mechanical and electrical interface)
- Low pressure drop air systems (mechanical (HVAC) and architectural interface
- Ability to modulate flows (mechanical and controls)